Occurrence, Detection, and Habitat Use of Larval Lamprey in Columbia River Mainstem Environments: Bonneville Tailwater and Tributary Mouths.

2011 Annual Report

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Table of Contents

List of Figures..2

List of Tables 3

Introduction..4

Methods...7

Results..13

Findings..16

Acknowledgements..20

References...21

List of Figures

Figure 1. Map of the study area in Bonneville Reservoir and tributary inputs of the Columbia River in 2011...10

Figure 2. Map of the study area in the Bonneville Dam tailwater of the Columbia River, 2011...11

Figure 3. Aerial photos of river mouth areas within Bonneville Reservoir surveyed for larval lamprey occupancy in 2011. 12

Figure 4. A schematic showing a section of the Columbia River divided into 30 x 30 m quadrats and associated UTM center points 13

Figure 5. Reach-specific detection probability given varying levels of sampling effort in the Bonneville Tailwater (BonTW) and tributary mouths (i.e., Hood River and Wind River) in 2011. Broken line represents 80% confidence of lamprey absence when not detected 14

Figure 6. Length-frequency histogram for larval lamprey captured at the Wind River mouth in 2011……..…………………………………………………………………..15

Figure 7. Klickitat River delta in Bonneville Reservoir in November 2011 during low Water……………………………………………………………………………………..19

List of Tables

Table 1. Total number of quadrats delineated, visited, sampled, and occupied and species present at different locations in the Bonneville Dam tailwater and tributary mouths within the Bonneville Reservoir, 2011...13

Table 2. Sediment mean percent in size categories (mm), and organic content in Bonneville Tailwater and tributary mouths in 2011. Standard errors are in parentheses...15

Table 3. Summary of detection rate for all mainstem larval lamprey work to date. 18

Introduction

Pacific lamprey *Entosphenus tridentatus* in the Columbia River Basin and other areas have experienced a great decline in abundance. They are culturally important to Native American tribes, are ecologically important within the food web, and their decline provides insight into the impact of human actions on ecological function (Close et al. 2002). Information is lacking on basic biology, ecology, and population dynamics required for effective conservation and management.

Pacific lampreys have a complex life history that includes a multiple year larval (ammocoete), migratory juvenile, and adult marine phase (Scott and Crossman 1973). Larvae and juveniles are strongly associated with stream and river sediments. Larvae live burrowed in stream and river sediments for multiple years after hatching, where they filter feed detritus and organic material (Sutton and Bowen 1994). Larvae metamorphose into juveniles from July to December (McGree et al. 2008) and major migrations are made downstream to the Pacific Ocean in the spring and fall (Beamish and Levings 1991). The sympatric western brook lamprey *Lampetra richardsoni* does not have a major migratory or marine life stage although larvae may be found considerable distances downstream (Jolley et al. *In press*) and adults may locally migrate upstream before spawning (Renaud 1997). For both species, the majority of the information on habitat preference of larvae comes from Columbia River Basin tributary systems (Moser and Close 2003; Torgersen and Close 2004; Stone and Barndt 2005; Stone 2006) and coastal systems (Farlinger and Beamish 1984; Russell et al. 1987; Gunckel et al. 2009).

Lamprey ammocoetes are known to occur in sediments of shallow streams but their use of larger river (i.e., >5th order [1:100,000 scale]; Torgerson and Close 2004) habitats in relatively deeper areas is less known. Downstream movement of larvae, whether passive or active, occurs year-round (Nursall and Buchwald 1972; Gadomski and Barfoot 1998; White and Harvey 2003). Anecdotal observations exist regarding larval lamprey occurrence in large river habitats mainly at hydropower facilities or in downstream bypass reaches (Hammond 1979; Moursund et al. 2003; Dauble et al. 2006; CRITFC 2008), impinged on downstream screens, or through observation during dewatering events. Occurrences at hydropower facilities are generally thought to be associated with downstream migration and specific collections of presumably migrating ammocoetes have been made in large river habitats (Beamish and Youson 1987; Beamish and Levings 1991). Sea lamprey *Petromyzon marinus* ammocoetes have been documented in deepwater habitats (up to 4.6 m) in tributaries of the Great Lakes, in proximity to river mouths (Hansen and Hayne 1962; Wagner and Stauffer 1962; Lee and Weise 1989; Bergstedt and Genovese 1994; Fodale et al. 2003*b*), and in the St. Marys River, a large river that connects Lake Superior to Lake Huron (Young et al. 1996). References to other species occurring in deepwater or lacustrine habitats are scarce (American brook lamprey *Lampetra appendix*; Hansen and Hayne 1962). A previous study of Pacific lamprey and *Lampetra* spp. use of mainstem habitats of the Willamette and Columbia rivers (Silver et al. 2008; Jolley et al. *In press*) indicated Pacific lamprey and western brook lamprey of a broad range in size found utilizing multiple areas of the Willamette River.

Sampling of larvae in deepwater (i.e., > 1.0 m) areas is a challenge because of specialized gear requirements as well as presumed patchy distributions. Successful sampling of deepwater areas for larval sea lamprey has occurred in tributaries to the Great Lakes and the Willamette River using a modified electrofisher with suction (Bergstedt and Genovese 1994, Jolley et al. *In press*). However, uncertainty associated with detection probabilities and capture efficiencies is often encountered. In addition, the issue of false absences in the estimation of occupancy for species that are rare or patchily distributed has been identified (Bayley and Peterson 2001; Peterson and Dunham 2003; MacKenzie et al. 2005). We have previously developed a statistically rigorous study design to evaluate whether lamprey occupy mainstem habitats of a large river (Willamette River; Jolley et al. *In press*). These methods included a generalized random tessellation stratified (GRTS) sampling approach combined with the calculation of detection probabilities that were used to inform the number of site visits required to achieve a specific certainty of lamprey absence (when not detected), and in making inferences about distribution from collected data. Detection probabilities also provide the venue for comparison and inference. Those results indicated detection of larvae in all areas except the Multnomah Channel. Lampreys were widespread and detected at depths up to 16 m. Detection probabilities were 0.08 (reach) and 0.23 (30 x 30 m quadrat). The sampling required for 80% confidence of lamprey absence when they were not detected was 17 quadrats (in the reach) and 6 subquadrats (in a quadrat). Differences in lamprey detection by depth were not detected. A wide range of sizes was collected (20-144 mm TL) indicating the likely occurrence of multiple ages of larvae. That study documented the first quantitative information on larval Pacific lamprey and *Lampetra* spp. occupancy in mainstem river habitats. That study also established the ability to effectively use the deepwater electrofishing technology and apply a statistically robust and rigorous sampling scheme to explore patterns of distribution, occupancy, and detection. Furthermore, these quantitative techniques formed a foundation for comparisons of lamprey occupancy and detection in other mainstem areas; the GRTS approach provides the venue for statistical inference.

Questions regarding the significance and extent of larval rearing in other large rivers remain. The Columbia River and associated tributaries may have been a significant source of Pacific lamprey. The basin is highly altered and river fragmentation poses serious threats to many areas in the basin (Luzier et al. 2011). The effect of dams and the altered habitats they create (e.g. reservoirs, scoured tailwaters) remains unknown. The Lower Willamette reach previously studied was downstream of any dam in the Willamette and Columbia rivers. To this end we continued an evaluation of larval lamprey occupancy in mainstem areas of the Columbia River associated with Bonneville Dam (Bonneville Reservoir and Bonneville Dam tailwater) to further document the presence of larval lampreys. Specifically, we wanted to evaluate patterns of occupancy and distribution above and below a major anthropogenic structure (i.e., Bonneville Dam) which alters the natural structure and function of the Columbia River (Jolley et al. 2011a). We were particularly interested in two non-natural habitats: reservoirs and tailwaters. Results from work conducted 2010 indicated presence of larval Pacific lamprey in Bonneville Reservoir (n=1; d=0.02) and a required sampling effort of 63 quadrats to be 80% certain of larval lamprey absence when they were not detected (given d=0.02). In the Bonneville Tailwater (~14 km reach below dam), no larvae were detected although 67 quadrats were sampled. Of 5 sites sampled in the Wind River mouth (within Bonneville Reservoir), one larva was detected. Preliminary evaluation of sediment samples indicated higher organic content in the Wind River mouth area compared to Bonneville Reservoir or Bonneville Tailwater and coarser substrates in the Bonneville Tailwater likely resulting from sediment starved water.

We continued this work in 2011, by expanding the Bonneville Tailwater reach examined as well as continuing to investigate occupancy at tributary mouths within Bonneville Reservoir. Tributaries have been speculated to be the source of the larvae; they often form alluvial fans of fine rearing habitat, and thus may have a higher concentration of larvae. In general, we documented presence or absence of larval Pacific and *Lampetra* spp. throughout the Bonneville

Reservoir and compared that to information from the Bonneville Dam tailwater and determine detection probabilities using a deepwater electrofisher. Our specific objectives were as follows:

1) Determine occupancy of lamprey larvae in a subsequent reach of the Bonneville Dam tailwater.
2) Determine the detection probability of larval lamprey in the Bonneville Dam tailwater with a deepwater electrofisher, given it was occupied.
3) Determine the detection probability of larval lamprey at tributary mouth areas within Bonneville Reservoir, with a deepwater electrofisher, given it was occupied.
4) Compare proportion of sites occupied to other habitat patches (i.e. reservoir, tailwater, Lower Willamette).
5) Describe the size distribution of larval lamprey.
6) Describe the species composition of larval lamprey.

Methods

We estimated occupancy of larval lamprey in the Columbia River within several explicit spatial scales by adapting an approach used by Peterson and Dunham (2003) and refined by the U.S. Fish and Wildlife Service (USFWS 2008) to evaluate patch occupancy and detection probability for bull trout *Salvelinus confluentus*. The approach was further applied to studies of larval lamprey in the Willamette and Columbia rivers (Jolley et al. *In press*, 2011a, 2011b). The approach has several requirements: 1) a site- and gear-specific detection probability (assumed or estimated); 2) the probability of presence at a predetermined acceptably low level (given no detection); and 3) random identification of spatially-balanced sample sites that allow estimation of presence and refinement of detection probabilities.

A reach-specific probability of detection, d_{reach}, was calculated as the proportion of quadrats (i.e., 30 m x 30 m sampling quadrat) occupied (i.e., larvae captured) by larval lamprey in the Lower Willamette River, an area known to be occupied. The posterior probability of reach occupancy, given a larval lamprey was not detected, was estimated as

$$(1)\ \mathrm{P}(F|C_o) = \frac{\mathrm{P}(C_o|F)\cdot\mathrm{P}(F)}{\mathrm{P}(C_o|F)\cdot\mathrm{P}(F) + \mathrm{P}(C_o|{\sim}F)\cdot\mathrm{P}({\sim}F)},$$

where P(F) is the prior probability of larval lamprey presence. Although we knew the reach was occupied with larval lamprey, P(F) of 0.5 (uninformed) was used to inform future study design (i.e., P[$F|C_o$]) in areas where larval lamprey presence is unknown. P(~F), or 1 – P(F), is the prior probability of species absence, and P($C_o|F$), or 1 – d, is the probability of not detecting a species when it occurs (C_0 = no detection; Peterson and Dunham 2003). Detection rates by river reach or river mouth were compared using the Chi-square test for differences in probabilities (Conover 1999).

Bonneville Reservoir is impounded by Bonneville Dam (RKm 234) and The Dalles Dam (RKm 314) is the next upstream hydropower project. The reservoir is 75 km long, 7,632-ha at full pool and is 22.6 m above sea level (Figure 1). The Bonneville Dam tailwater reach was broadly defined as that portion of the mainstem Columbia River below Bonneville Dam but upstream of any significant tributary inputs where stream order was greater than 3 (i.e., Sandy River and Washougal River). The tailwater was sampled 13 September 2011 to 15 September 2011, from the vicinity of Skamania Island (RKm 217) to the east end of Steigerwald National Wildlife Refuge (RKm 204; Figure 2); a reach that was immediately downstream of a reach sampled in 2010 (Jolley et al. 2011a). Sampling occurred in summer and early fall when water velocities were presumably the lowest and most conducive to sampling.

Bonneville Reservoir tributary mouth areas were generally sampled in March-April 2011 (although the majority of the White Salmon River mouth was sampled in September). The tributary mouths examined were the Hood River, Klickitat River, White Salmon River, and Wind River (Figure 1). A tributary mouth area was defined as the wetted area contained by 0.5 km semi-circle from the point where center of the channel of the tributary meets Bonneville Reservoir (Figure 3).

A sampling event consisted of using a deepwater electrofisher (Bergstedt and Genovese 1994) in a 30 m x 30 m quadrat. This quadrat size was selected based on the previous experience of sea lamprey researchers in the Great Lakes (M. Fodale, USFWS, personal communication) as their sampling approach evolved from a systematic to adaptive approach (Fodale et al. 2003*a*). A description of the complete configuration of the deepwater electrofisher is given by Bergstedt and Genovese (1994). The bell of the deepwater electrofisher was lowered from a boat to the river bottom. The electrofisher delivered three pulses DC per second at 10% duty cycle, with a 2:2 pulse train (i.e., two pulses on, two pulses off). Output voltage was adjusted at each quadrat to maintain a peak voltage gradient between 0.6 and 0.8 V/cm across the electrodes. Suction was produced by directing the flow from a pump through a hydraulic eductor prohibiting ammocoetes from passing through the pump. Suction began approximately 5 seconds prior to shocking to purge air from the suction hose. Shocking was conducted for 60 seconds, and the suction pump remained on for an additional 60 seconds after shocking to ensure collected ammocoetes passed through the hose and emptied into a collection basket (27 x 62 x 25 cm; 2 mm wire mesh). The sampling techniques are described in detail by Bergstedt and Genovese (1994) and were similar to those used in the Great Lakes region (Fodale et al. 2003*b*).

We used a Generalized Random Tessellation Stratified (GRTS) approach to select sampling quadrats in a random, spatially-balanced order (Stevens and Olsen 2004). We developed a layer of 30 m x 30 m quadrats using ArcMap 9.3 (Environmental Systems Research Institute, Redlands, California) which was overlaid on the entire Bonneville Reservoir and Bonneville tailwater (Figure 4). There were 20,881 quadrats in the tailwater reach (from Skamania Island to Steigerwald National Wildlife Refuge) and river mouth areas had a range of quadrats (353-694) due to variable configurations of the terrestrial/aquatic interface (Table 1). The Universal Trans Mercator (UTM) coordinates representing the center point of each quadrat were determined. The lowest numbered quadrats within a selected stratum were selected from the previously generated GRTS procedure to maintain a random, spatially-balanced sample design. This approach was used to generate an unbiased sample design that would allow the quantification of detection probabilities. The quadrats were ordered sequentially as they were selected in the GRTS approach and the lower numbered quadrats were given highest priority for sampling. Initially, we set a goal of 34 quadrats for the tailwater reach and tributary mouths which is twice the estimated number to be 80% certain of lamprey absence when not detected (as estimated from the Willamette River where d=0.07).

Collected lampreys were anesthetized in a solution of tricaine methanesulfonate (MS-222), identified as Pacific lamprey or *Lampetra* spp. according to caudal pigmentation (Goodman et al. 2009), and classified according to developmental stage (i.e., larvae, juvenile, or adult). Lampreys were measured (TL in mm), placed in a recovery bucket of fresh river water, and released after resuming active swimming behavior. Length-frequency histograms were constructed for each species to describe size structure.

Concurrent to each sampling event a sediment sample was taken from the river bottom by using a Ponar bottom sampler (16.5 cm x 16.5 cm). A 500 mL sample was labeled, placed on ice, and returned to the lab. Samples were oven-dried for 12 hours at 100°C to remove all water. Sediment size was characterized by weighing the component portions of the sample that collected on a set of sieves (opening sizes: 37.5 mm, 19 mm, 9.5 mm, 1 mm, 0.5 mm, and remainder less than 0.5 mm). Percent organic content of replicate samples was determined using loss-on-ignition methods (Heiri et al. 2001) by combusting organic material at 500-550°C for six hours.

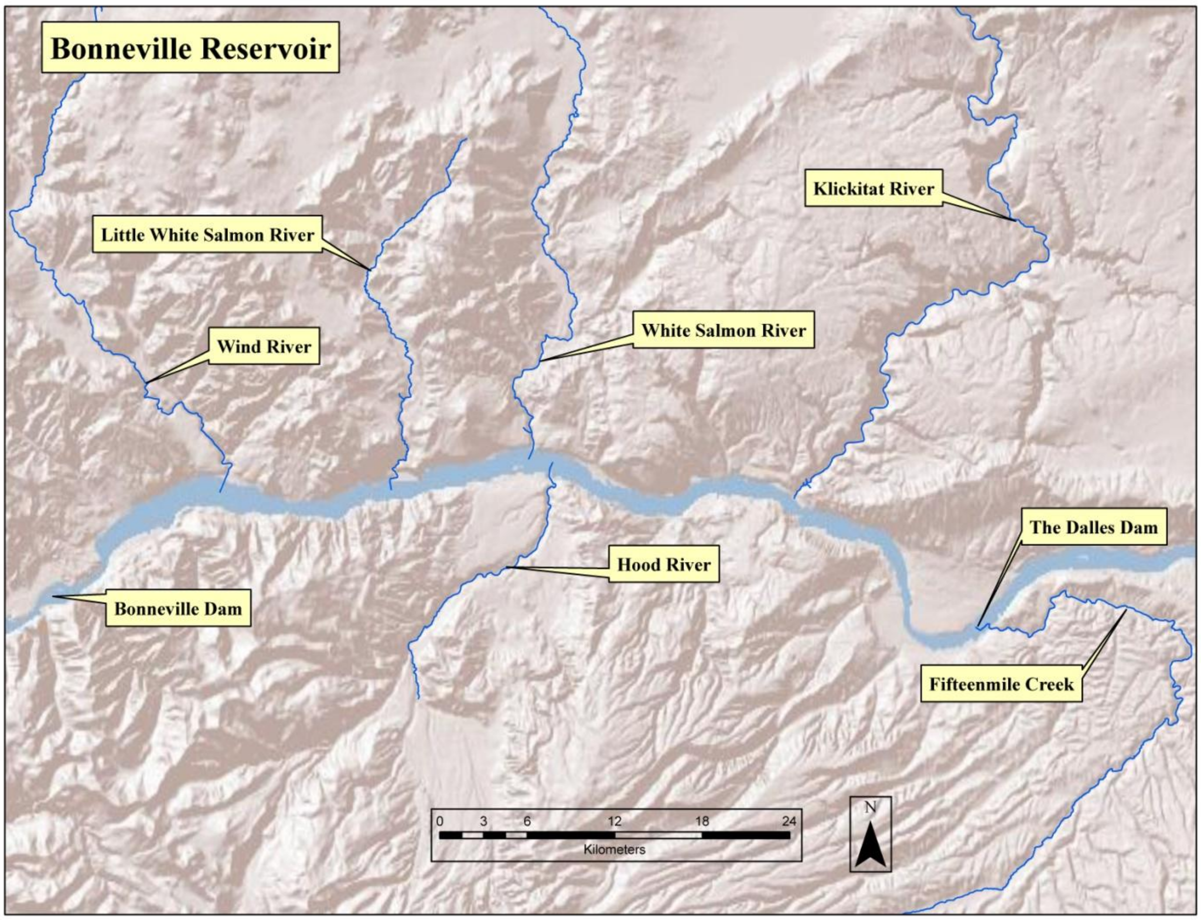

Figure 1. Map of the study area in Bonneville Reservoir and tributary inputs of the Columbia River in 2011.

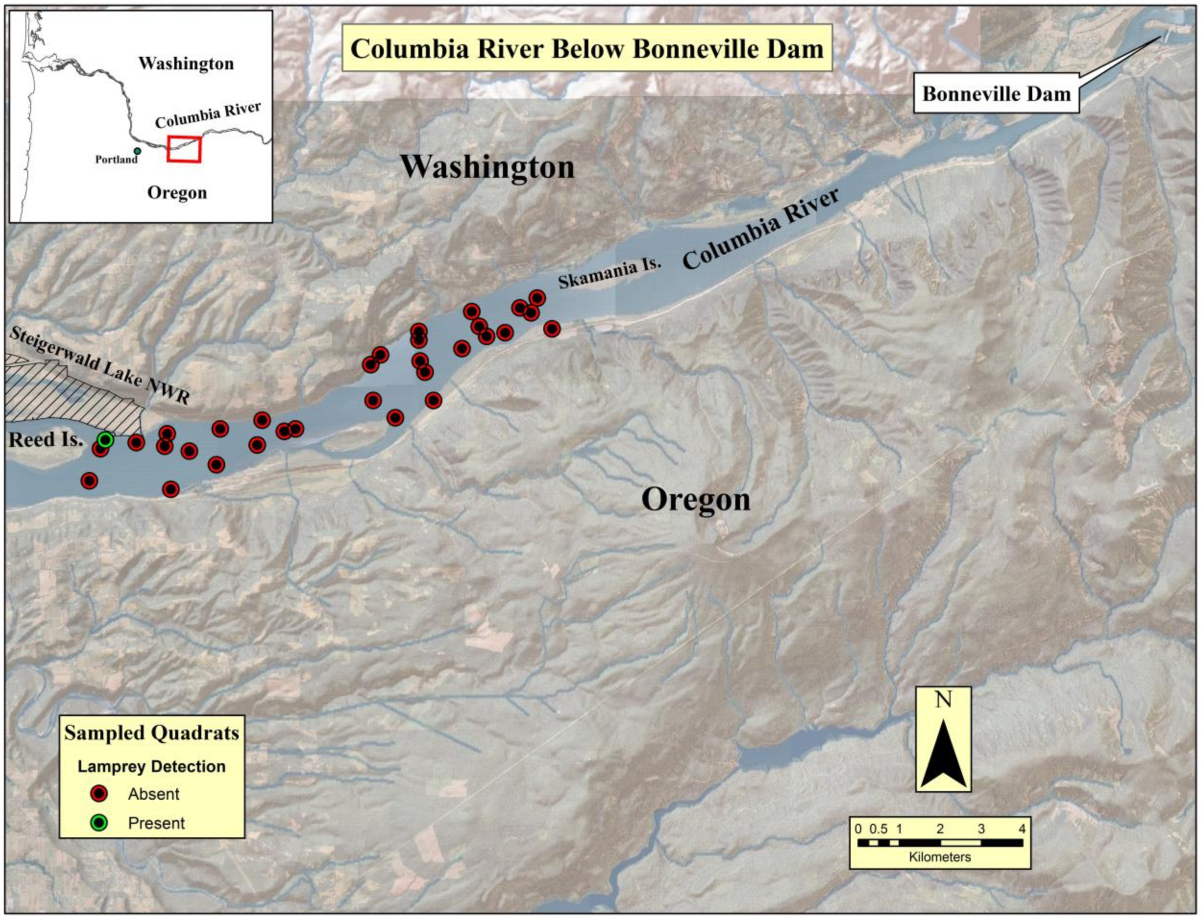

Figure 2. Map of the study area in the Bonneville Dam tailwater of the Columbia River and quadrats sampled in 2011.

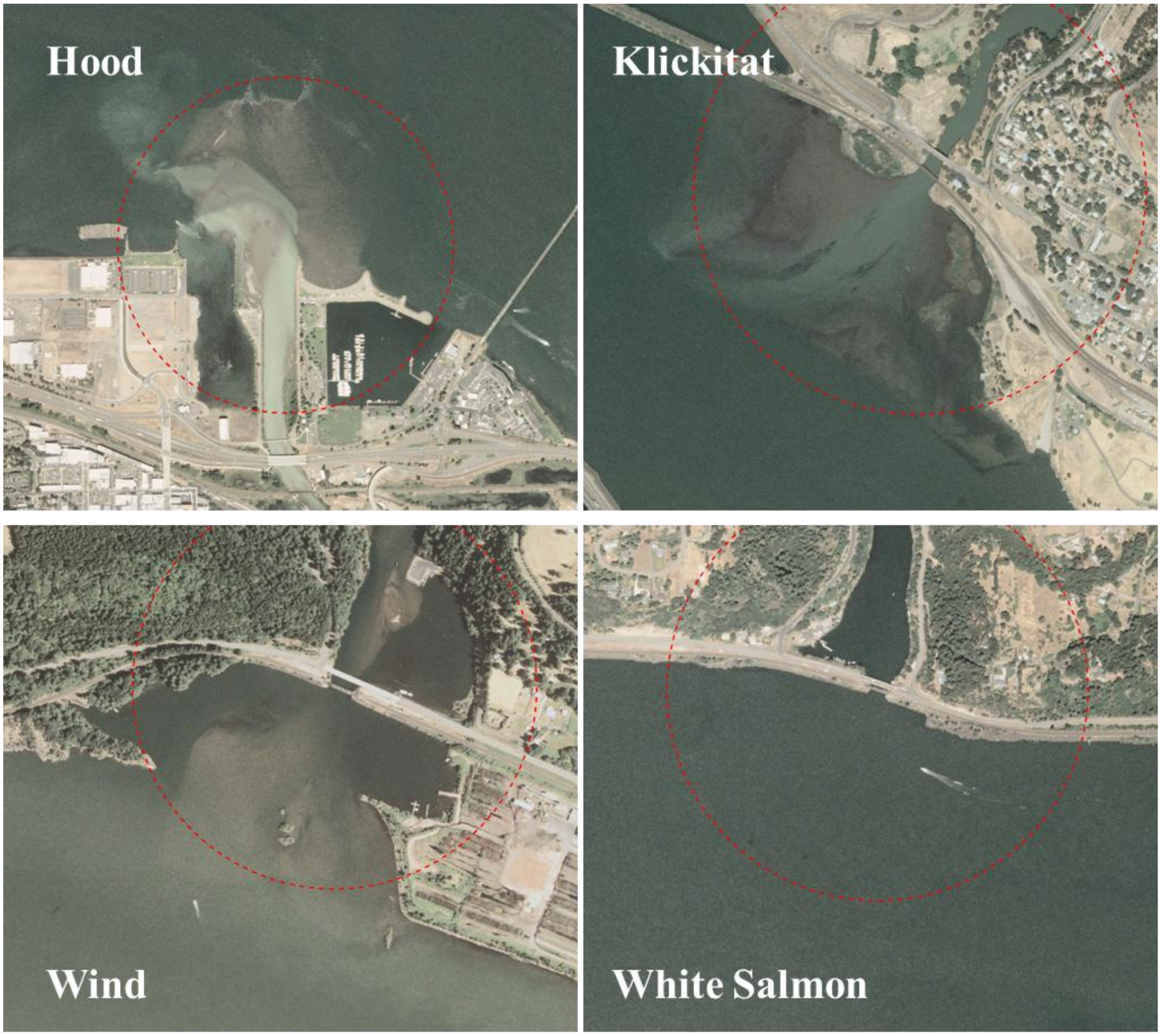

Figure 3. Aerial photos of tributary mouth areas within Bonneville Reservoir (0.5 km from confluence) surveyed for larval lamprey occupancy in 2011.

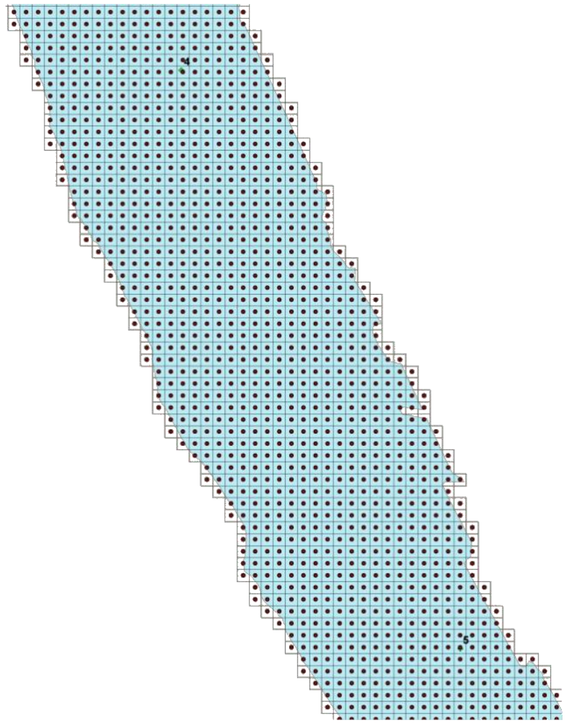

Figure 4. A schematic showing a generic section of the Columbia River divided into 30 m x 30 m quadrats and associated UTM center points.

Results

A total of 35 quadrats were visited in Bonneville Tailwater of which, 32 (91%) were sampled and 3 (9 %) were not sampled because they were not feasible (dewatered conditions). Overall, one larval western brook lamprey (TL=58 mm) was detected at 1 (3%) of the quadrats sampled in this reach (Table 1). This quadrat was near the Washington shore near the east end of Steigerwald National Wildlife Refuge at a depth of 0.6 m (Rkm 204; Figure 2).

Table 1. Total number of quadrats delineated, visited, sampled, and occupied and species present at different locations in the Bonneville Dam tailwater and tributary mouths within the Bonneville Reservoir, 2011.

	Quadrats								
Reach	Total	Visited	Sampled	Occupied	*d*	Pacific lamprey	Western brook lamprey	Unid	Total
Bonneville Dam tailwater	20,881	35	32	1	0.031	0	1	0	1
Hood River mouth	694	44	34	2	0.059	1	1	0	2
Klickitat River mouth	359	39	34	0	0.000	0	0	0	0
White Salmon River mouth	423	47	34	0	0.000	0	0	0	0
Wind River mouth	353	34	34	10	0.294	22	9	6	37

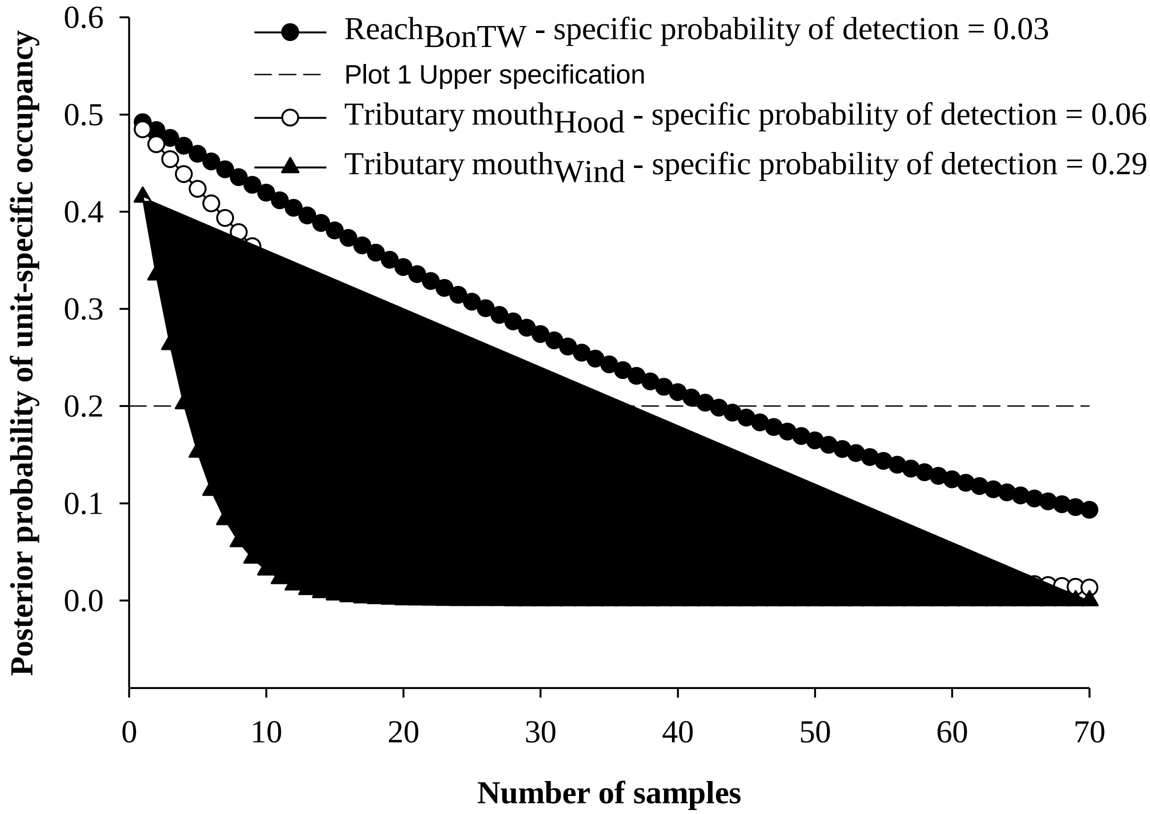

Figure 5. Reach-specific detection probability given varying levels of sampling effort in the Bonneville Tailwater (BonTW) and tributary mouths where larvae were detected (i.e., Hood River and Wind River) in 2011. Broken line represents 80% confidence.

Thirty-four quadrats were sampled within each river mouth area (Table 1). Pacific lamprey and western brook lamprey larvae were detected in the Hood River mouth (n=2 larvae, *d*=0.06) and the Wind River mouth (n= 37 larvae, *d*=0.29). In the Hood River mouth one Pacific lamprey (TL=79) and one western brook lamprey (TL=106) were collected. In the Wind River mouth, Pacific lamprey (60%), western brook lamprey (24%), and unidentified lamprey (16%) were collected and TL ranged from <20 mm to 152 mm (Figure 6). Unidentified lampreys either escaped through the mesh basket or were too small to identify. Larvae were found between 0.6 and 6.1 m. The proportion of quadrats occupied differed among river mouths (chi-square = 24.8, df=3, P<0.0001). Specifically, detection was higher at the Wind River mouth than either the Klickitat River mouth or White Salmon River mouth, where no larvae were detected (chi-square = 11.7, df=1, P=0.0006, Bonferroni correction, alpha=0.008).

In Bonneville Tailwater, 31 sediment samples were analyzed. Mean percent organic content was 1.5% (SE ± 0.2). Mean percent organic content in the tributary mouths ranged from 0.8 (White Salmon River) to 8.3 (Wind River, Table 2). Organic content was significantly higher in the Wind River mouth than any other location (ANOVA, F=9.95, df=4, P<0.0001). Sediment particle sizes were generally larger in the White Salmon River mouth (Table 2). Bedrock or hard bottom was detected at 22 sites (65%) at the White Salmon River mouth and at 1 site (3%) at the Wind River mouth.

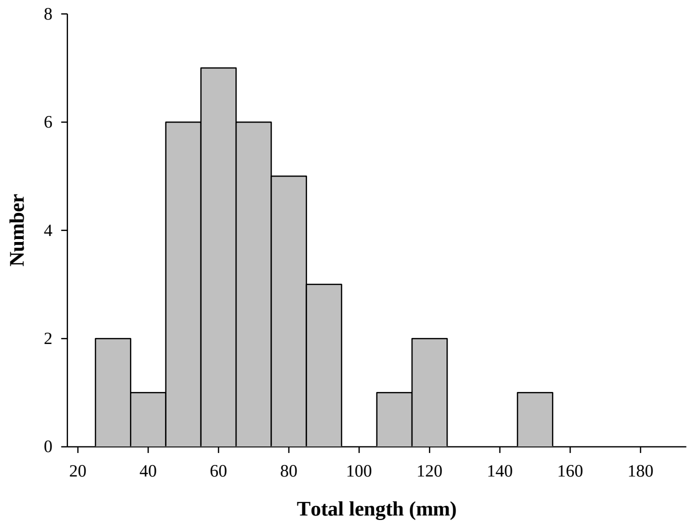

Figure 6. Length-frequency histogram for larval lamprey captured at the Wind River mouth in 2011.

Table 2. Sediment mean percent in size categories (mm), and organic content in Bonneville Tailwater and tributary mouths within Bonneville Reservoir in 2011. Table does not include areas of large cobble or bedrock. Standard errors are in parentheses.

	Mean percent particle size (mm)							
Reach	>37.5	37.5-19.0	19.0-9.5	9.5-1.0	1.0-0.5	<0.5	Mean percent organic content	Number
Bonneville Tailwater	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	1.3 (0.5)	6.4 (2.5)	92.3 (2.6)	1.5 (0.2)	31
Hood River mouth	0.0 (0.0)	0.9 (0.7)	0.5 (0.3)	11.8 (2.5)	20.4 (3.0)	66.4 (5.1)	1.4 (0.2)	34
Klickitat River mouth	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	5.3 (1.1)	31.2 (4.5)	63.5 (5.4)	1.3 (0.2)	34
White Salmon River mouth	11.2 (5.9)	24.1 (10.7)	6.1 (4.2)	4.3 (1.7)	19.6 (8.5)	26.4 (10.8)	0.8 (0.1)	6
Wind River mouth	0.0 (0.0)	2.6 (2.6)	2.2 (1.1)	13.8 (3.5)	19.9 (4.0)	61.4 (6.3)	8.3 (1.9)	34

Findings

Larval Pacific lampreys occupy Bonneville Reservoir. Our findings are similar to those of studies conducted in the Great Lakes, where larval sea lamprey and American brook lamprey *Lampetra appendix* have been found in lentic areas (Hansen and Hayne 1962), deepwater tributaries (Bergstedt and Genovese 1994; Fodale et al. 2003*b*), and large rivers (Young et al. 1996) and corroborate our earlier findings (Jolley et al. *in press*, 2011a). It is unknown if the larval lampreys actively migrated from headwater tributaries, were passively washed out of upstream habitats, hatched in the mouths of tributary rivers or the reservoir, or some combination of these. The reservoirs created by many dams on the Columbia River may create habitats (e.g., relatively slower velocity, increased sediment deposition) that didn't exist prior to dam construction or were likely less abundant. Larval lamprey may use these areas at a disproportionally higher rate than they did prior to dam construction. Conversely, the habitats directly below dams (e.g., increased scouring, suppression of natural flow regime) may be inhospitable to larval lamprey use. Historically, it is conceivable that larval lamprey used the large river habitats more evenly in the Columbia River where natural rearing habitats occurred (e.g., natural depositional areas, side channels). Studies of ammocoete movement, as well as passage routes and survival rates at Columbia River dams would significantly improve our understanding of the relative importance and potential impacts of mainstem residency on larval lamprey populations. Overall, larval lamprey distribution and habitat usage of mainstem areas in the Columbia River, including above and below hydropower projects, remains largely uninvestigated.

Larval lampreys were first detected in the Bonneville tailwater reach 28 km downstream of the dam. In 2010, we failed to detect larval lampreys in the immediate 18 km below Bonneville Dam (excluding the first 3 km directly below the dam due to unfeasible velocities; Jolley et al. 2011a). Relatively coarse substrate in that reach suggested scouring from the dam operations. Sediment samples collected in 2011 in the lower tailwater reach indicated the presence of finer substrates that were presumably appropriate for larval rearing. No significant tributary inputs (stream order >3) were present in the entire tailwater reach studied thus far, although larvae have been detected in some of the smaller tributaries (i.e., Hardy Creek; J. Johnson, USFWS, personal communication). However, the relative lack of tributary inputs might decrease the probability that any spawning in those tributaries may contribute little to the occupancy, and thus detection, of larvae in the tailwater reach. If larval lampreys have a passive or active downstream movement pattern it is possible that the presence and operations of Bonneville Dam affect this movement, further reducing occupancy. Two larger (stream order > 3) tributaries enter the Columbia River downstream of our study reach (i.e., Washougal River and Sandy River) that are known to contain populations of larval lamprey (J. Jolley, unpublished data; USFS 1996). A plausible hypothesis might be that detection rates of larval lamprey would increase in the mainstem Columbia River below these rivers as the mainstem accumulates more larvae from the tributaries.

Detection rates of larval lamprey have ranged, to date, from 0.02 to 0.32 covering all current and previous work in the Columbia and Willamette rivers (Table 3). Original objectives were to input empirical detection rates into the detection probability models to estimate reach-specific levels of sampling effort for defined levels of certainty of larval absence when not detected. Using a relatively moderate to low detection rate of 0.07 (within known occupied areas) led to a sampling effort of 17 quadrats necessary to achieve 80% certainty of lamprey absence when they are not detected. We propose using this level of effort as a starting point for determining occupancy of other reaches. The GRTS approach allows increasing the sample effort, while maintaining a random and spatially-balanced design, when warranted (i.e., low detection). Detection of larval lamprey was higher at some tributary mouths in Bonneville Reservoir (see Jolley et al. 2011a) suggesting a potential increased local population size (relative to other areas; Royle and Nichols 2003), enhanced rearing conditions in these areas, tributaries serving as source populations for larvae in the mainstem, or higher capture efficiency in these conditions. The Wind River mouth had the highest detection rate and also the highest organic content of sediment of all areas examined. The detection rate at the Wind River mouth was one of the highest observed in all of our mainstem larval research to date (Table 3). In addition, multiple larvae were captured at 15% of the quadrats at the Wind River mouth. High occupancy rates coupled with different levels of occupancy (i.e., n>1 individual detected) introduce the ability to incorporate multi-state occupancy models which are an extension of standard occupancy models (MacKenzie et al. 2006; Nichols et al. 2007). These models can be particularly useful to model habitat effects on occupancy. Future work might couple additional measures of habitat variables to be used as co-variates to the detection probability models.

Table 3. Summary of detection rate for all mainstem larval lamprey work to date.

Year	Reach	*d*	Pacific lamprey	Western brook lamprey	Unid	Total	Source
2009	Lower Willamette River	0.07	5	6	1	12	Jolley et al. *In press*
2010	Bonneville Reservoir	0.02	1	0	0	1	Jolley et al. 2011a
	Bonneville Tailwater	0.00	0	0	0	0	
2011	Bonneville Tailwater	0.03	0	1	0	1	Current report
	Hood River mouth	0.06	1	1	0	2	
	Klickitat River mouth	0.00	0	0	0	0	
	White Salmon River mouth	0.00	0	0	0	0	
	Wind River mouth	0.29	22	9	6	37	
	Lower Klickitat River	0.26	13	0	2	15	Jolley et al. xx
	Lower White Salmon River	0.29	5	11	3	19	
	Lower Wind River	0.32	13	9	4	26	

The Klickitat River is known to have a population of larval lamprey in the system (P. Luke, Yakama Nation Fisheries, personal communication) and larvae were detected in the lowest reaches of this river (Jolley et al. 2012). Our failure to detect larvae in the Klickitat mouth was unexpected. It had an extensive delta area with fine sediments of presumably suitable size for larval burrowing and rearing. Larvae may be present but if so are likely at a density too low to detect or capture efficiency was reduced by unknown reasons. Larvae may not colonize areas that become dry throughout the year. Larvae were present at the Hood River mouth but detectability was low. Powerdale Dam on the Hood River (less than 1 km from the mouth) was removed in 2009 and the ability of lamprey to pass it is unknown. It is also unknown if adult Pacific lampreys have recolonized further upstream or if successful spawning has taken place. It is possible that density of larvae in the basin is low and potentially related to our low detection rates at the mouth. The mouths of the Wind, Klickitat, and Hood rivers are subject to seasonal dewaterings from flow fluctuations. Dewatering is mild in the Wind and relatively severe in the Klicktat and Hood river mouths (Figure 6). These mouths were sampled in the spring during relatively high water when the entire delta was submerged.

The absence of larval lamprey at the White Salmon River mouth was expected. There was very little suitable habitat at the mouth and the area was dominated by deep water, swift flows, and mainly bedrock or coarse substrate. Condit Dam on the White Salmon River has blocked natural sediment movement downstream for many years and blocked all upstream fish passage. The dam was breached in October 2011 and will be completely removed in the next year. Sediment from the impounded Northwestern Reservoir was allowed to rapidly flush downstream. Formation of new river delta will be a dynamic process and will be monitored

Figure 7. Dewatered Klickitat River delta in Bonneville Reservoir in November 2011.

along with the Lower White Salmon River as part of a concurrent and related project (Jolley et al. 2012). This work generated baseline empirical detection and habitat data (prior to the dam breaching).

Several future topics warrant examination. It has been estimated that approximately 50% of adult lampreys encountering a Columbia River mainstem dam fishway may successfully pass (Keefer et al. 2009). Furthermore, mainstem passage is a severe threat to lamprey populations in the Middle and Upper Columbia Basin and population size and occupancy is thought to be low (Luzier et al. 2011). Broadly, there may be a negative relationship between the density of larvae and the distance upstream the mainstem (i.e., increased number of dams). Fewer adults returning and spawning would result in fewer larvae produced. Examining occupancy and detection of larvae, both broadly within the upstream impoundments, and at river mouth areas might further illuminate this notion. For example, the Deschutes River Basin has a known population of lamprey (Gadomski and Barfoot 1998; Graham and Brun 2002; Fox and Graham 2008) and it enters the Columbia River in The Dalles Pool, the next impoundment upstream from Bonneville Reservoir. It is possible that detection will decrease in this river mouth area and decrease in the impoundment as a whole compared to that found in Bonneville Reservoir. Examining these areas downstream of Bonneville Dam may also be useful and increased detection rates would be expected. Examining lamprey occupancy at river mouth areas throughout the season may provide insight on the seasonal influence on occupancy at a local scale. The influence of fluctuating water levels at river mouths also warrants attention. Fluctuating water levels have been implicated in stranding of fish (Bradford 1997; Adams et al. 1999; Irvine et al. 2009). Lamprey may use these areas seasonally and understanding those patterns would assist in determining management objectives (e.g., flow and water level management).

Overall, lamprey larvae of multiple sizes and species occupy a broad range of areas within the Columbia River mainstem; we provide empirical evidence for this. These areas should not be overlooked as relevant to the conservation and management of these imperiled species. This topic has been largely ignored and further research and monitoring is needed to address larger uncertainties in population trends, recruitment, and mortality.

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